Tokamak Disruptions

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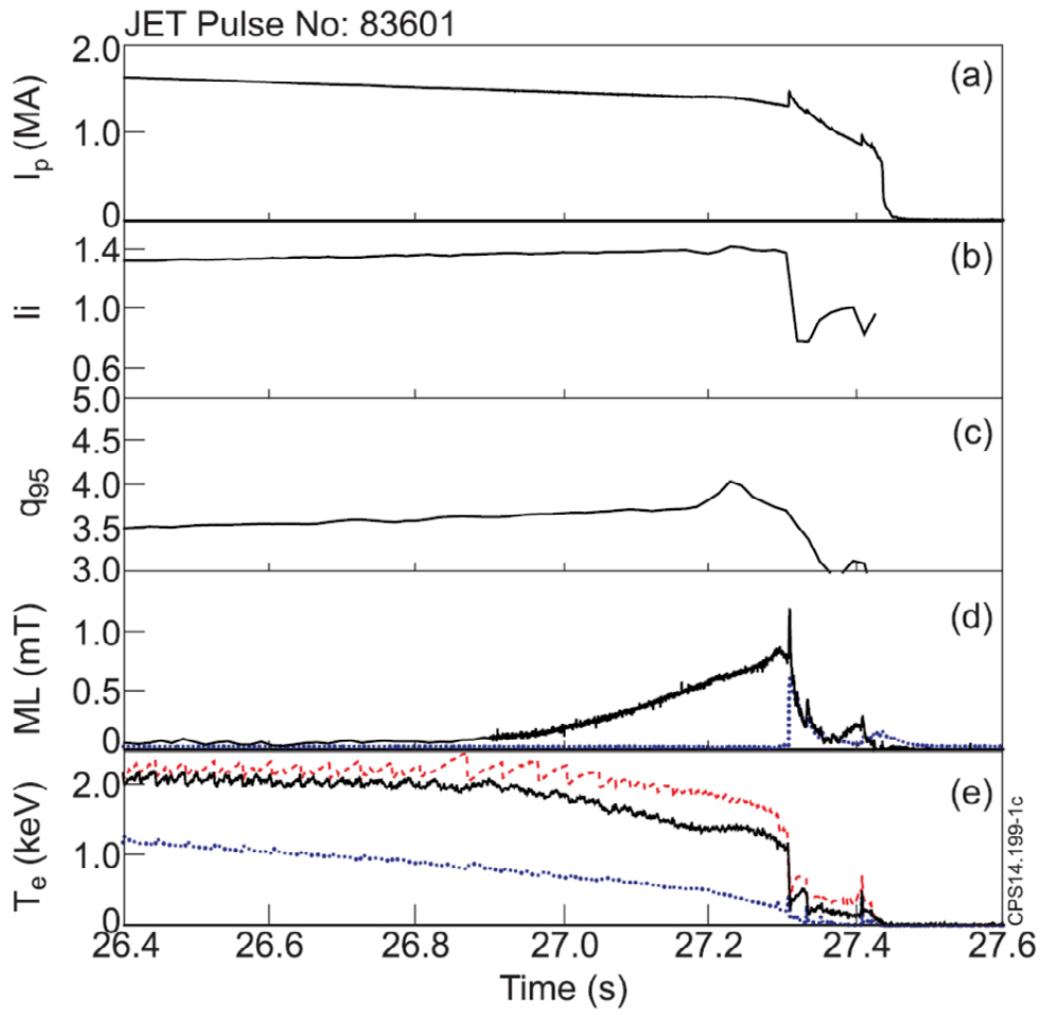
1. What does a disruption look like?

$$\ell_i = \frac{2\kappa}{1+\kappa^2} \frac{\int_0^{\Psi_t} I^2(\psi_t) \frac{d\psi_t}{\psi_t}}{I^2(\Psi_t)}$$



de Vries P.C. *et al*, *Nucl. Fusion* **<u>56</u>** 026007 (2016)

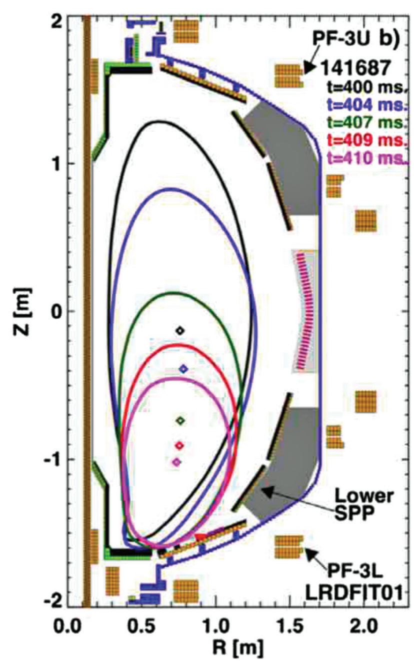
2. Why are tokamaks disruption prone?

A sudden loss of plasma pressure or a flattening of the current profile causes a tokamak plasma to drift toward the chamber walls; the required vertical field is

$$B_v \approx -\frac{1}{2}\left(\frac{a}{R_0}\right)^2 \left(\iota_I \ell_0 + \iota_{tot}\beta_p\right) B_0;$$

$$\ell_0 = \ln\left(\frac{8R_0}{a}\right) + \ell_i - \frac{3}{2} \sim 2; \qquad\qquad \iota_{tot} \equiv \iota_I + \iota_{ex}.$$

A stellarator plasma undergoes a shift $\frac{\delta_\perp}{a} = \frac{a}{2R_0}\frac{\iota_I \ell_0 + \iota_{tot}\beta_p}{\iota_{ex}}$ and doesn't hit the wall.



Gerhardt, Nucl. Fusion 53, 023005 (2013)

3. How do disruptions place ITER at risk?

1. Power load on the divertor: The rapid cooling during the thermal quench, $\lesssim 1$ ms, would place an unacceptable power on the divertor unless almost all of the power is radiated uniformly.

2. Forces from induced wall currents: Induced currents in the walls: (a) a cosinusoidal current I_v to maintain a fixed normal (vertical) field to the walls, (b) a net poloidal current G_w due to displaced toroidal magnetic flux, (c) an equal but opposite toroidal current I_t to the change in the net toroidal current in the plasma.

3. Forces from halo currents: Halo currents flow along the magnetic field in the plasma edge and close by flowing through the wall. Arise when the plasma becomes too kink unstable to be stabilized by a perfectly conducting wall. *Happens when plasma position control is lost and plasma drifts into the wall, ~ 150 ms, before the current can be quenched. The edge safety factor drops due plasma scrape-off to $q_{edge} \approx 2$, which gives a strong kink.* Rotational enhancement of forces and arcing are also issues.

4. Multi-megaampere currents of relativistic electrons striking walls: The loop voltage required to remove the poloidal flux ≈ 75 V·s in 150 ms in ITER gives $V_\ell = 500$ V. Electrons can runaway when $V_\ell > V_{ch} \approx (2.9\text{ V})(n_e/10^{20}\text{m}^{-3})$.

A current quench time of 50 ms is considered acceptable for ITER for which $V_\ell \approx 1500$ V.

4. What are the relativistic electron issues?

Damage from currents or relativistic electrons are the disruption issue that can most endanger the ITER mission. ***ITER must be operated as conservatively as necessary to ensure a major relativistic electron incident occurs no more than once in a thousand pulses (less than once a year).***

Relativistic current exponentiates $\frac{dI_{rel}}{dt} = \frac{I_{rel}}{\psi_{ex}}\frac{d\psi_p}{dt}$, where $\psi_{ex} \approx (0.30\text{ MA})\mu_0 R_0$.

Can amplify an initial (or seed) current by up to 10^{16} times.

Two types of sources of seed electrons:

a. Remnant seed

Passing and trapped electrons from the pre-thermal-quench Maxwellian that have not lost their kinetic energy by collisions, which takes $\lesssim 15$ ms, or been lost along open magnetic field lines. *Only source in non-nuclear phase of ITER operations.*

b. Steady production

Tritium decay and Compton scattering by gamma rays from irradiated walls provide a steady source of seed electrons, but *only after nuclear operations begin in ITER.*

Dangerous level of poloidal flux

For the remnant seed from hot tail electrons, ITER is in danger of a transfer of a large fraction of the plasma current to relativistic electrons unless either the cooling time or the time magnetic surfaces are open is $\gtrsim 15\,ms$.

Neither of these conditions is adequate in the nuclear phase of ITER operations when the poloidal flux between any magnetic surface and the chamber wall satisfies $\psi_p > \Psi_{dang}$, and a major danger exists of transferring an unacceptable fraction of the plasma current to relativistic electrons.

$$\Psi_{dang} \equiv \ell_f \psi_{10}$$
$$\ell_f \equiv \log_{10}\left(\frac{\text{\# of relativistic electrons required to carry current}}{\text{\# of seed electrons}}\right)$$
$$\psi_{10} \equiv \ln 10 \times \psi_{ex} \approx (0.70\text{ MA})\mu_0 R_0 \approx 5.5\text{V}\cdot\text{s in ITER} \qquad (1)$$

Tritium decay $\ell_f \approx 7.8$, so $\Psi_{dang} \approx 43$ V·s. Runaway can be blocked when $n_e \gtrsim 10^{21}$ m^{-3}.

Compton scattering ℓ_f is 6.3 to 9.3 at $n_e = 10^{20}$ m^{-3}, but ℓ_f is 3.6 to 6.6 at $n_e = 500 \times 10^{20}$ m^{-3}, and $\Psi_{dang} \approx 20$ to 51 V·s. Expected γ-ray flux 10^{15} to 10^{18}m^{-2}s^{-1} is based on unpublished data and is the major uncertainty.

Poloidal flux planned for ITER is ≈75 V·s, and its mission requires $\gtrsim$50 V·s.

5. How do impurities affect disruptions?

Impurities (carbon, Z=6; neon, Z=10; and argon Z=18) are needed to cool plasma sufficiently for the plasma current to be quenched before the plasma drifts into the walls, within 150 ms, and to spread the thermal quench energy evenly over the walls through radiation.

Carbon-covered walls provide the impurities in many existing tokamaks. In ITER and in recent JET experiments, the walls are metal and impurities must be injected. *Disruptions can be initiated by the accidental or intentional injection of impurities.*

Unfortunately, the radiation curves of impurities naturally lead to rapid cooling, $\lesssim 1$ ms, which rapidly brings the parallel electric field force, $eE_{||}$ above the drag force of the background electrons eE_{ch}, far shorter than the $\lesssim 15$ ms it takes tail electrons to follow the Maxwellian to a lower temperature.

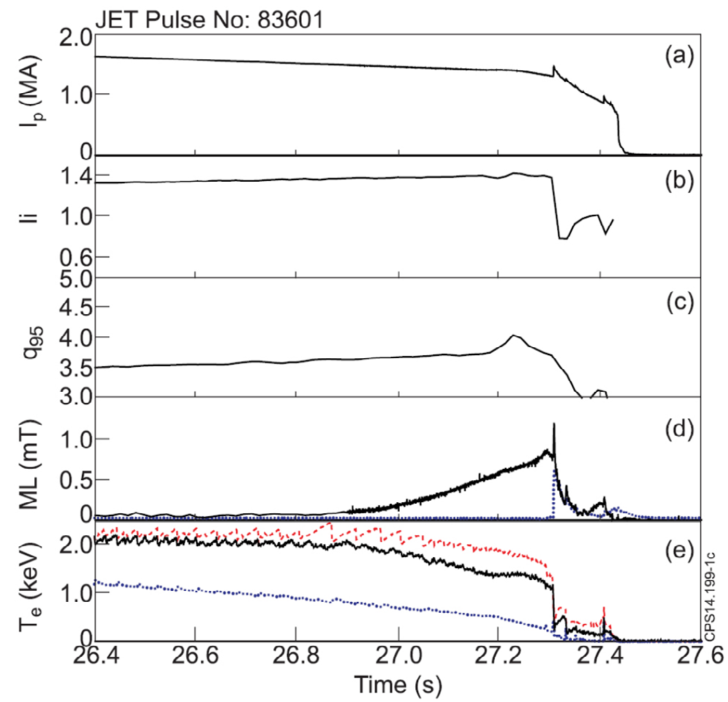
The mechanism by which impurities rapidly reach the center of plasmas, $\lesssim 1$ ms, during a disruption is not understood.

The drag force, eE_{ch}, or Connor-Hastie loop voltage, $V_{ch} = 2\pi R_0 E_{ch}$ is $V_{ch} \approx 2.9$ V $n_e/(10^{20}\ \mathrm{m}^{-3})$ can in principle be made bigger than the actual loop voltage during the current quench, $V_\ell \gtrsim 500$ V, by raising the hydrogenic density—impurities would radiate too much. Even electrons bound in impurity ions contribute to the drag force.

6. How does breaking of magnetic surfaces affect disruptions?

The sudden drops in the internal inductance ℓ_i and the current spikes that occur in association with the thermal quench imply a large fraction of the magnetic surfaces are destroyed and the current profile is flattened during a period $\lesssim 1$ ms.

The sudden change in time scale is evidence of a fast magnetic reconnection. Natural evolution time of islands (Rutherford time) is ≈ 200 ms.



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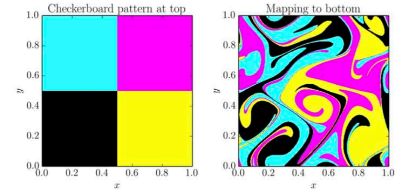
The flattening of the current profile and the loss of plasma pressure during the thermal quench removes the drive for plasma kinking. As seen in NIMROD and JOREK simulations, the plasma should quickly return to an axisymmetric state *unless the normal magnetic field to the walls can be made strongly non-axisymmetric.*

Fast magnetic reconnection

Even after an ideal evolution, $\partial\vec{B}/\partial t = \vec{\nabla}(\vec{u}\times\vec{B})$, a circular tube of magnetic flux at one location will generically have a perimeter that increases exponentially in length as the tube is followed through space.



This exponentiation implies magnetic field line connections, even on the scale of the plasma radius, are sensitive to non-ideal effects on an exponentially small scale.

The small non-ideal spatial scales are $\delta_\eta = \sqrt{\tau_{spike}\eta/\mu_0}$ or $\delta_{skin} = c/\omega_{pe}$. For ITER, both δ's are ~ 0.5 mm.

The reconnection of magnetic field lines that are carrying a differing parallel current density $j_{||}$ causes $j_{||}/B$ to relax Alfvénically. The temporal scale that must be resolved is $2\pi R_0/V_A \sim 5$ μs in ITER.

$$\vec{\nabla}\cdot\vec{j} = 0 \text{ implies } \vec{B}\cdot\vec{\nabla}\frac{j_{||}}{B} = \vec{B}\cdot\vec{\nabla}\times\frac{\vec{f}}{B^2}, \text{ where } \vec{f} = \vec{j}\times\vec{B}$$

is the electromagnetic or Lorentz force. When $\vec{f} = \rho_0 d\vec{v}/dt$, relaxation of $j_{||}/B$ along the magnetic field is by Alfvén waves, $V_A = B/\sqrt{\mu_0\rho_0}$.

Fast magnetic reconnection conserves magnetic helicity, $\int\psi_p(\psi_t)d\psi_t$.

Direct effect of open magnetic field lines on runaway

Relativistic passing electrons on open magnetic field lines strike the walls too quickly to produce an important relativistic current.

Trapped electrons remain available to provide an important seed if the magnetic surfaces re-form before the trapped electrons have slowed down, ~ 15 ms.

The absence of runaway electrons in JET with ITER-like walls when they might be expected may well be due to the opening up of the magnetic surfaces through fast magnetic reconnection.

Axisymmetric helicity-conserving simulations

When magnetic field lines in a stochastic region behave diffusively, the evolution of the plasma current obeys

$$\frac{\partial I}{\partial t} = -\frac{2}{L}\mathcal{D}[I] \quad \text{where} \quad L(\psi_t) \equiv \frac{2\psi_t}{I}\iota(\psi_t) \approx \frac{2\kappa}{1+\kappa^2}\mu_0 R_0, \quad \text{and} \quad \iota = \frac{1}{q(\psi_t)}:$$

$$\mathcal{D}[I] \equiv -\psi_t \frac{\partial}{\partial \psi_t}\left\{\mathcal{R}_\psi \frac{dI}{d\psi_t} - \frac{\partial}{\partial \psi_t}\left(\psi_t \Lambda_m \frac{\partial^2 I}{\partial \psi_t^2}\right)\right\}.$$

$\mathcal{R}_\psi$ is plasma resistivity and Λ_m gives the helicity conserving current relaxation. An axisymmetric equilibrium code is only needed for a more accurate L.

7. Does disruption prediction help?

Disruptions in a fusion reactor are generally viewed as unacceptable, which means with a frequency of less than a decade. For the ITER mission to be achievable, major runaway incidents should have a frequency of less than once a year.

Disruption prediction is critical to achieving these goals, but only when the prediction time is longer than the time required to appropriately steer the plasma to avoid a disruption or to largely mitigate its consequences.

For worst-case scenarios, this is the time it takes to terminate a plasma starting from maximum operating parameters without inducing a disruption. Little research has been done, but the L/R time of tens of minutes may be required.

The shortest prediction time that could possibly be of benefit is the time required to take an action that might affect the evolution of the plasma. For example, it requires approximately 20 ms for presently designed systems for pellet injection on ITER to deposit any particles in the plasma.

Since particle injection is the only disruption mitigation strategy under intense investigation for ITER, 20 ms is often specified as the required prediction time. This is despite the low confidence that the particle injection schemes can prevent incidents involving multi-megaampere currents of relativistic electrons.

8. What is the status of disruption protection for ITER?

Particle injection can probably provide adequate protection to ITER against all effects except relativistic electrons currents, but further research is required.

The seriousness of the relativistic electron issue has been known to ITER management for more than twenty years, but remarkably little has been done assessing it.

The most important period is the thermal quench with its associated ℓ_i drop and current spike, approximately two orders of magnitude shorter than the current quench, $\approx$150 ms.

Although important data is routinely collected on this short period, little is published, far less is published showing the measured evolution on a relevant time scale, and essentially no physics analyses, or purposed-planned experiments have been carried out. Review articles essentially do not exist.

We do know: (1) Existing MHD codes do not have a current spike as large as that seen in experiments and generally enhance the resistivity well above its experimental value.

(2) Helicity conservation gives a larger current spike than is seen in experiments and that this can be explained by a much larger spatial average resistivity $< \eta >$ than the central resistivity. Since a fast magnetic reconnection can flatten $j_{||}/B$ out to the chamber walls, it is $< \eta >$ in the region enclosed by the walls that is appears to be relevant.